TYL-FJPPL: HEP_04

Cosmological tests of fundamental physics in inflationary universe

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Fawzi Boudjem Geneviève Bélanger
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Student; Vivian Poulin

Members

LAPTh

- Pasquale Serpico: Neutrino cosmo, Astroparticle phys, BBN
- Fawzi Boudjem: Dark matter, Higgs, Precision EW phys
- Geneviève Bélanger: Dark matter, Higgs, Precision EW phys
- Kengo Shimada: Inflation, Baryogenesis
- Vivian Poulin: CMB, Astroparticle phys (→Johns Hopkins U.)

KEK

- Kazunori Kohri: Inflation, Neutrino cosmo, Primordial BH, BBN
- Satoshi Iso: Higgs, Baryogenesis, Inflation, Dark energy
- Taro Mori: Inflation (Sokendai)
- Nagisa Hiroshima: Dark matter, Astroparticle phys (U. Tokyo)

Purpose of the project

To investigate the fundamental physics through **cosmological probes**

Fundamental physics

- Hierarchy and EW vacuum (in)stability issues
- Neutrino physics with baryo(lepto)genesis scenario
- Nature of dark matter

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Simplest model

Cosmological probes
- Observational signals of inflation: CMB
- Gravitational waves from cosmological phase transition
- Primordial black hole and BBN

In progress
K.Kohri, N.Hiroshima, V.Poulin, P.Serpico

arXiv: 1704.04955
S.Iso, P.Serpico, K.Shimada

Gravitational waves from QCD-EW phase transition

Based on arXiv: 1704.04955
S. Iso, P. Serpico and K. Shimada

- Minimal **U(1) B-L** extension of the SM

Z' : **B-L** gauge boson

N_i : Right-handed neutrino

canceling gauge anomaly

Seesaw
Leptogenesis
Dark matter

Spontaneous
symmetry breaking

Majorana
mass

ϕ : **B-L** Higgs

Inflaton (large or small)

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Inflaton (large or small)

with **classical scale invariance**

S.Iso, N.Okada and Y.Orikasa (2009)

An assumption motivated by hierarchy & vacuum (in)stability arguments

W.A.Bardeen (1995)

We focus on **cosmological** consequences.

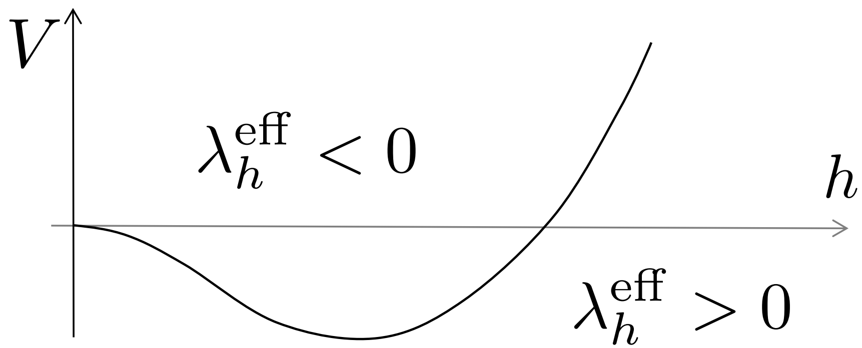
Gravitational waves from QCD-EW phase transition

- Classically scale invariance

$$V(h) = \frac{\lambda_h}{4} h^4 - \frac{\mu^2}{2} h^2$$

No dimensionful parameter

Coleman-Weinberg (CW) mechanism in the SM?



does **NOT** work in the SM.

$$\beta_{\lambda_h} < 0$$

Gravitational waves from QCD-EW phase transition

- Classically scale invariance

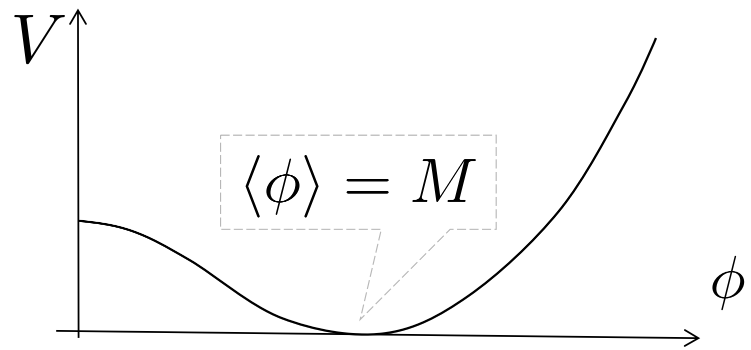
$$V(\phi, h) = \frac{\lambda_h}{4} h^4 + \frac{\lambda_{\text{mix}}}{4} \phi^2 h^2$$

$\lambda_{\text{mix}} < 0$

Coleman-Weinberg (CW) mechanism with a new scalar ϕ (**B-L** Higgs)

$$+ \frac{\lambda_\phi^{\text{eff}}(\phi)}{4} \phi^4$$

$\beta_{\lambda_\phi} > 0$



Gravitational waves from QCD-EW phase transition

- Classically scale invariance

$$V(\phi, h) = \frac{\lambda_h}{4} h^4 + \frac{\lambda_{\rm mix}}{4} \phi^2 h^2 + \frac{\lambda_\phi^{\rm eff}(\phi)}{4} \phi^4$$

$\langle \phi \rangle = M$

$\lambda_{\rm mix} < 0$

$\beta_{\lambda_\phi} > 0$

Coleman-Weinberg (CW) mechanism
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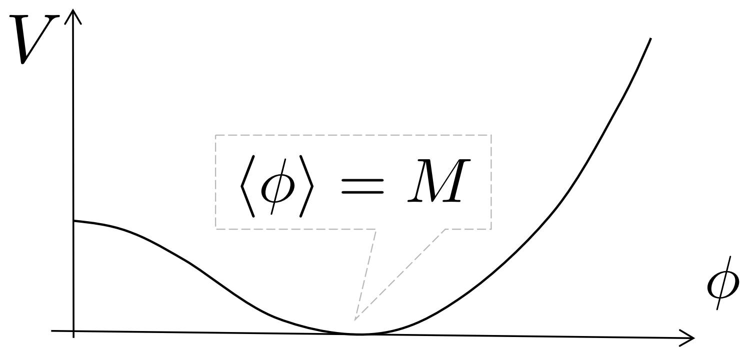
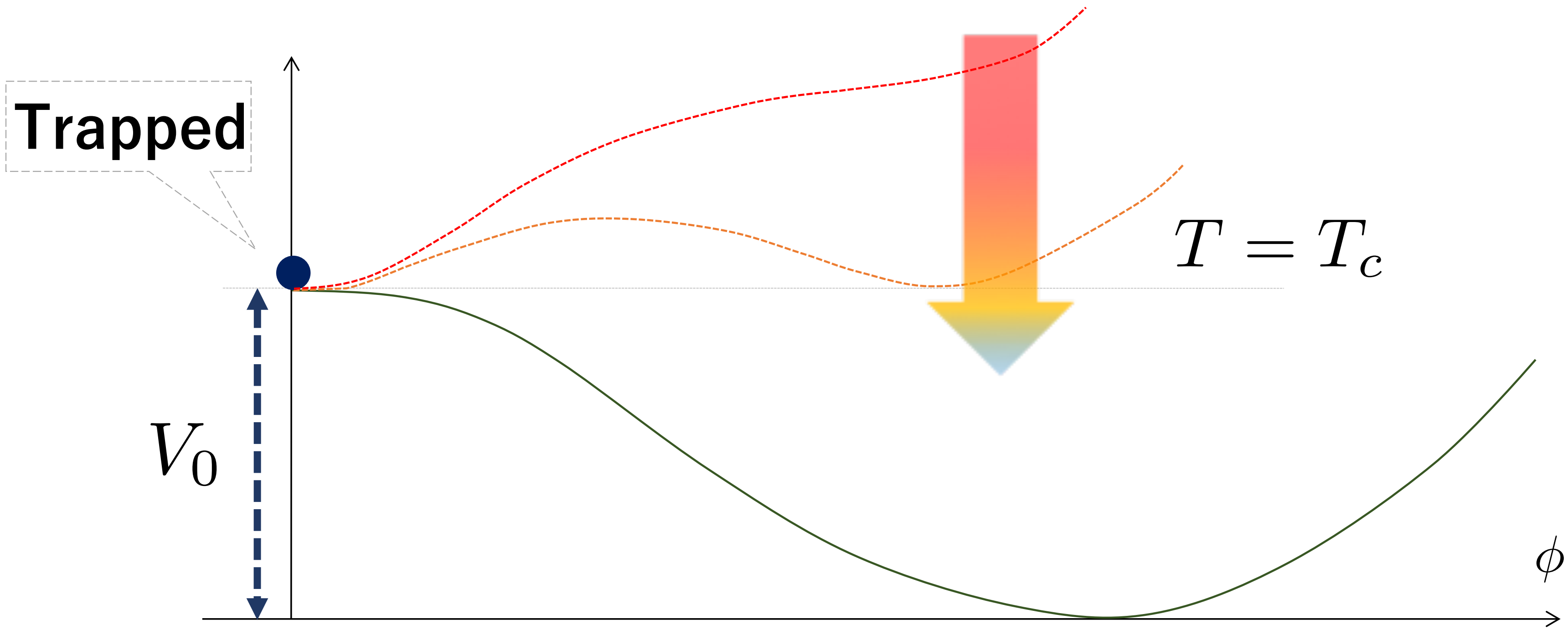


B-L SB triggers
Electroweak SB

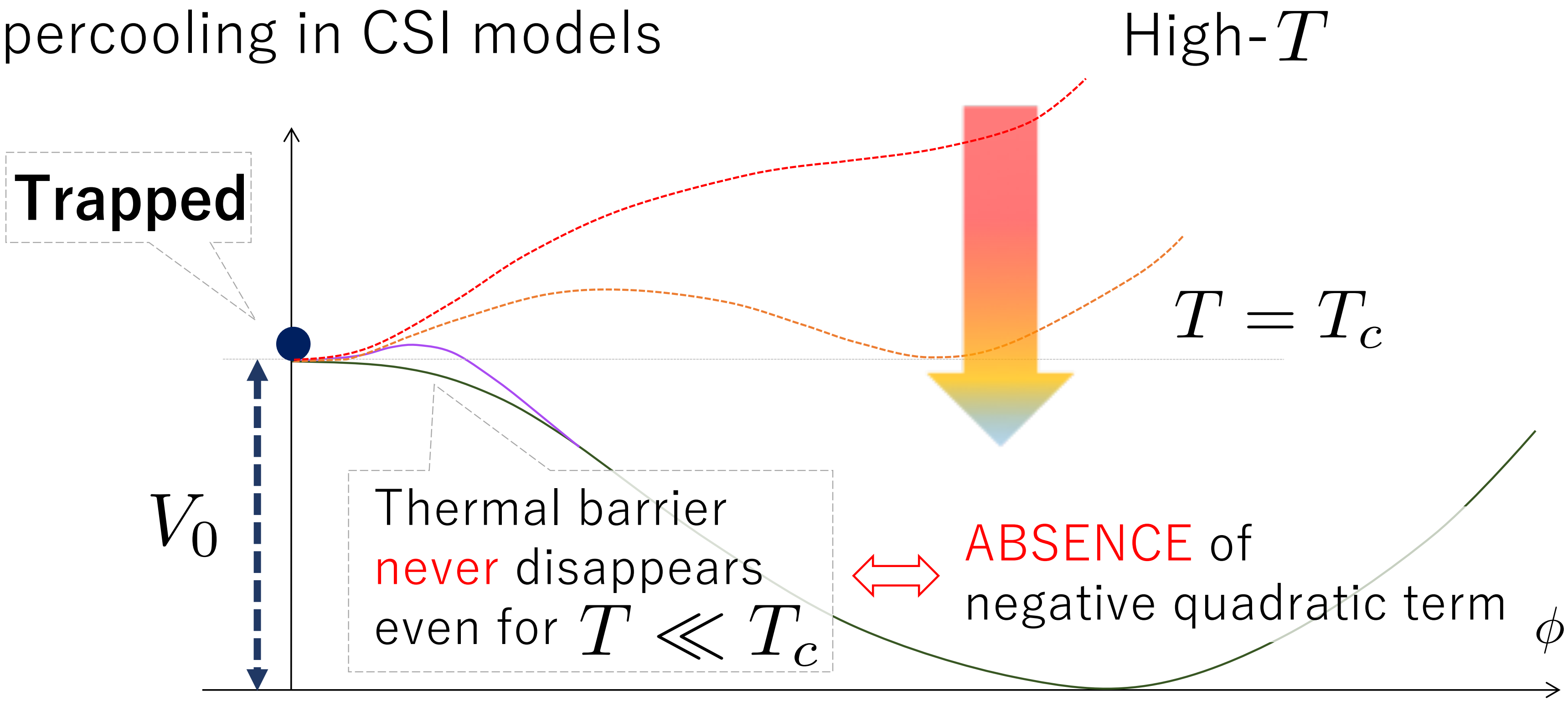
Gravitational waves from QCD-EW phase transition

- Supercooling in CSI models



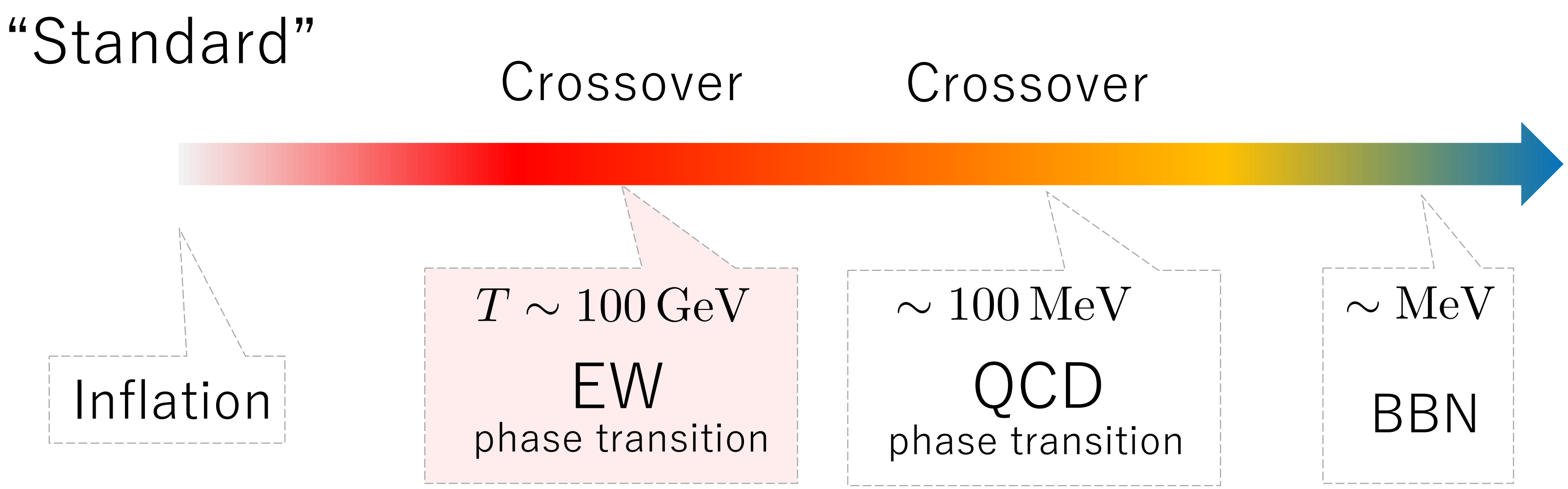
Gravitational waves from QCD-EW phase transition

- Supercooling in CSI models

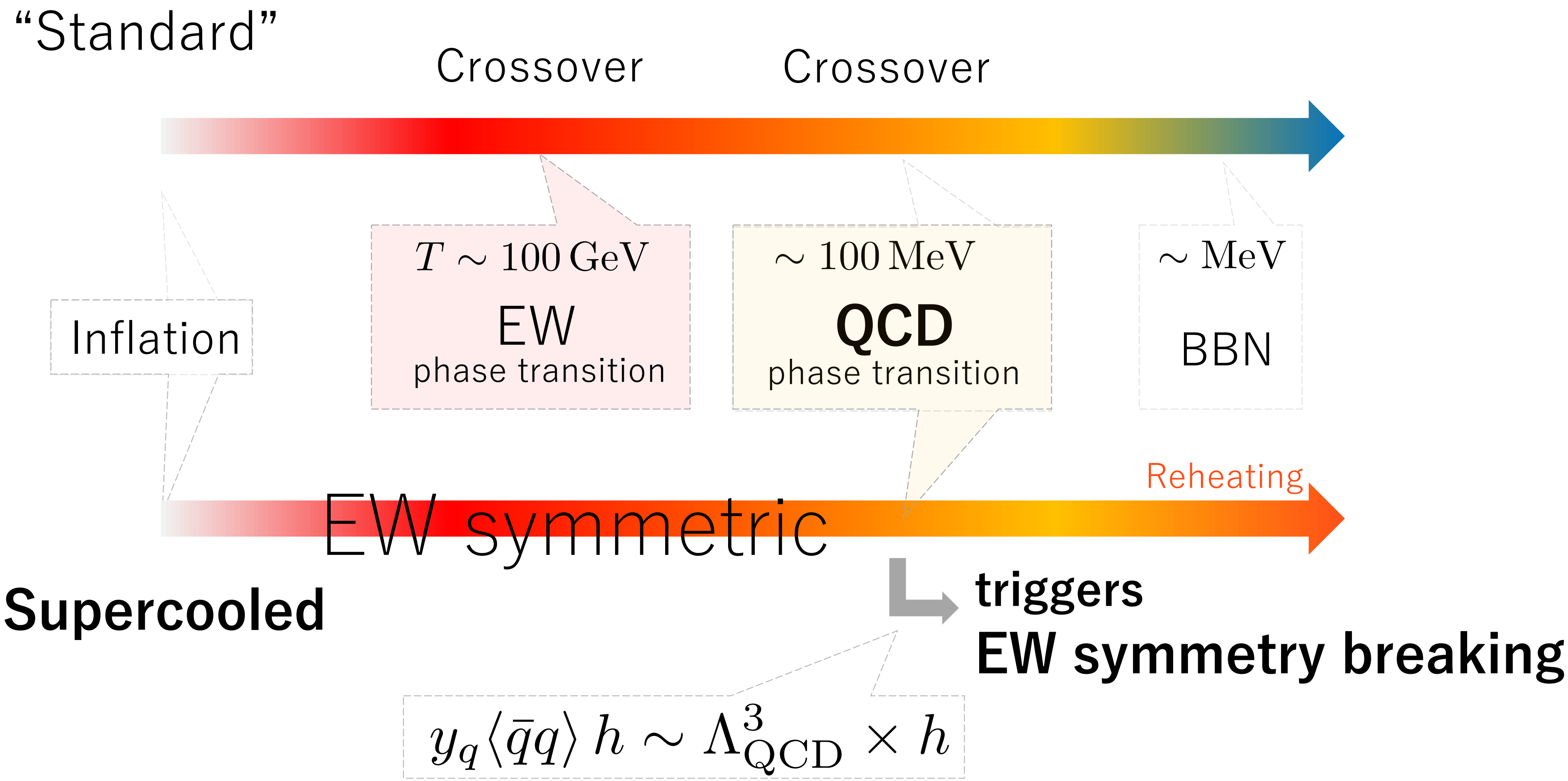


Universe remains in the **meta-stable** state (Supercooling) $\Leftrightarrow$ **EW**SB (**B-L** SB) does NOT take place

Gravitational waves from QCD-EW phase transition



Gravitational waves from QCD-EW phase transition



Gravitational waves from QCD-EW phase transition

- QCD phase transition

In the **supercooled** scenario

$N_f = 6$ massless quarks (in EW symmetric phase $h = 0$)

➡ **1st-order** phase transition (for $N_f \geq 3$) R.D.Pisarski F.Wilczek (1983)

Gravitational waves from QCD-EW phase transition

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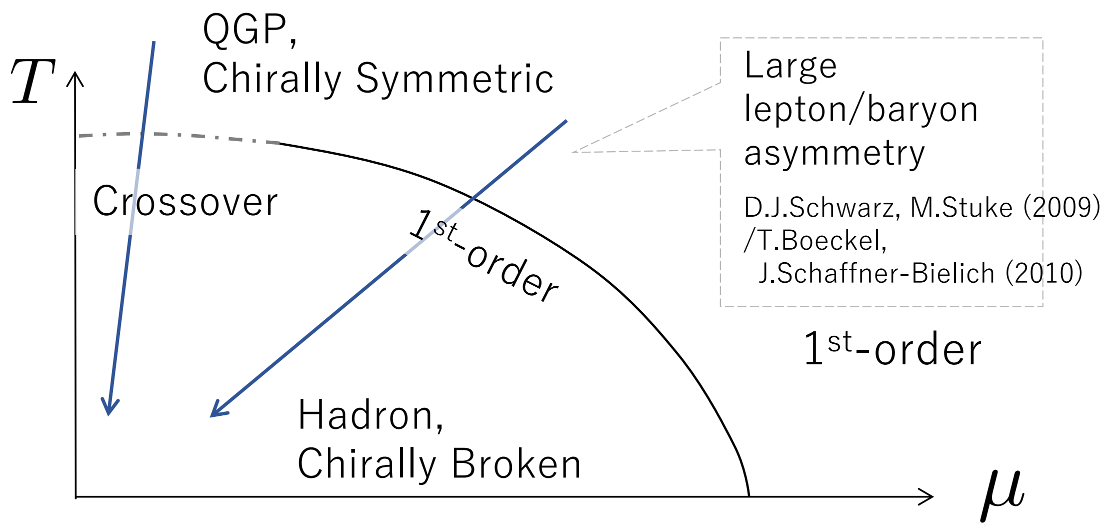
In the “standard” scenario

$$N_f = 2 + 1$$

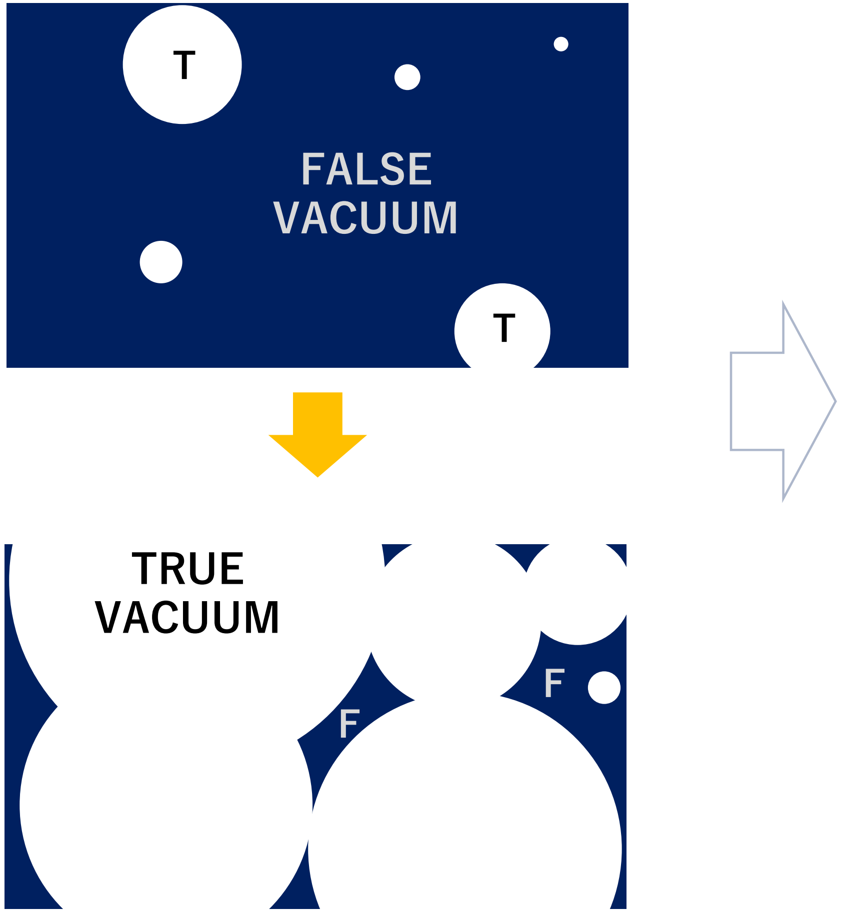
$m_{u,d} \ll \Lambda_{\rm QCD}$ $m_s \sim \Lambda_{\rm QCD}$

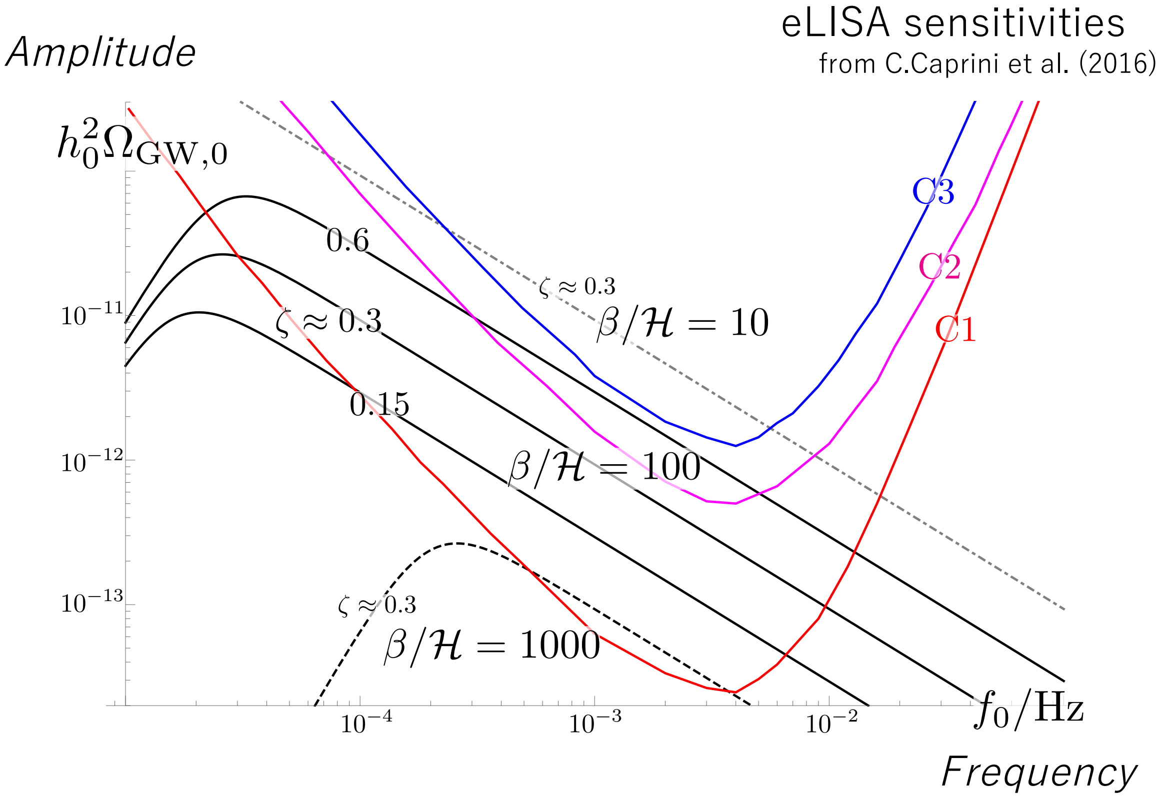
⇨ Crossover



Gravitational waves from QCD-EW phase transition

- GWs from bubble collisions





($\zeta \sim T_{\rm rh}/V_0^{1/4}$: reheating efficiency)

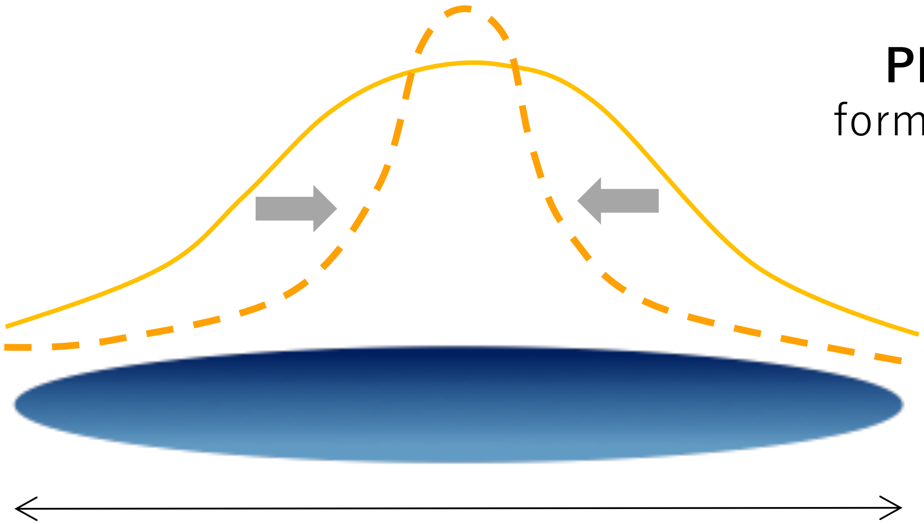
CMB limits on accreting primordial black holes

In progress

K.Kohri, N.Hiroshima, V.Poulin, P.Serpico

Density perturbation

$\delta > \delta_c \sim 0.3$ (in RD era)



Horizon scale $\sim 1/H \sim m_{\rm pl}/T_{\rm form}^2$

PBH formation

$$M_{\rm pbh} \sim 20\, M_\odot \times \left(\frac{100{\rm MeV}}{T_{\rm form}}\right)^2$$

$$\sim 10^{15}\, g \times \left(\frac{6\times 10^8 {\rm GeV}}{T_{\rm form}}\right)^2$$

$$M_{\rm pbh} \gtrsim 10^{-18}\, M_\odot \sim 10^{15}\, g$$

Stable at present, contribute to $\Omega_{\rm CDM}$

CMB limits on accreting primordial black holes

PBHs accrete and **heat up matter**

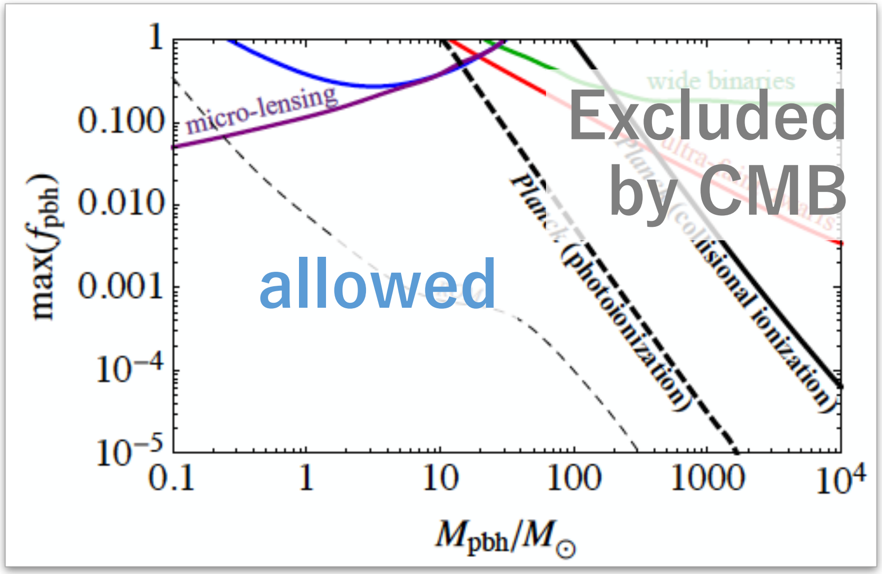
emit photons to **ionize the cosmic gas**.

M.Ricotti, J.P.Ostriker, K.J.Mack (2008)

Spherical accretion

Y. Ali-Haimoud, M. Kamionkowski (2017)

$\Omega_{\rm PBH}/\Omega_{\rm DM}$



(stellar size) *PBH mass*

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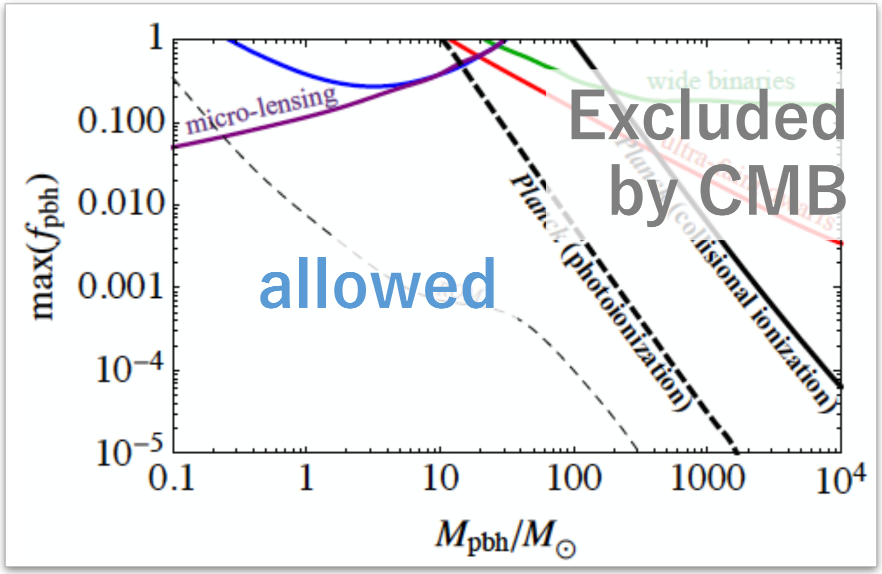


(stellar size) *PBH mass*

- What if accretion **disk** is formed?

  : more natural situation under
  the tidal effects from the nearest PBH

- $T \sim 0.1\,{\rm MeV} \sim 10^9{\rm K}$ ➡ Thermonuclear reactions

  Primordial Black hole Nucleosynthesis (PBN)

Summary

- We assumed a simple, motivated model.
- Delayed EWPT ➡ QCD triggered EWSB takes place.

  Sizable gravitational waves.
  New particles lighter than EW scale.

✓ Phase transition dynamics on multi-dimensional field space
✓ Electroweak baryogenesis?
✓ Low-scale supercooling stage (inflationary expansion).

⇨ Large density fluctuation ⇨ Stellar mass PBH production

- CMB limits on primordial black hole with accreting disk?
- Primordial black hole nucleosynthesis?

Merci

감사합니다

Backup

$V_0^{1/4} \sim m_{Z'}$

S.Iso, N.Okada and Y.Orikasa (2009)

Minimal **U(1) B-L** model

ϕ : **B-L** Higgs

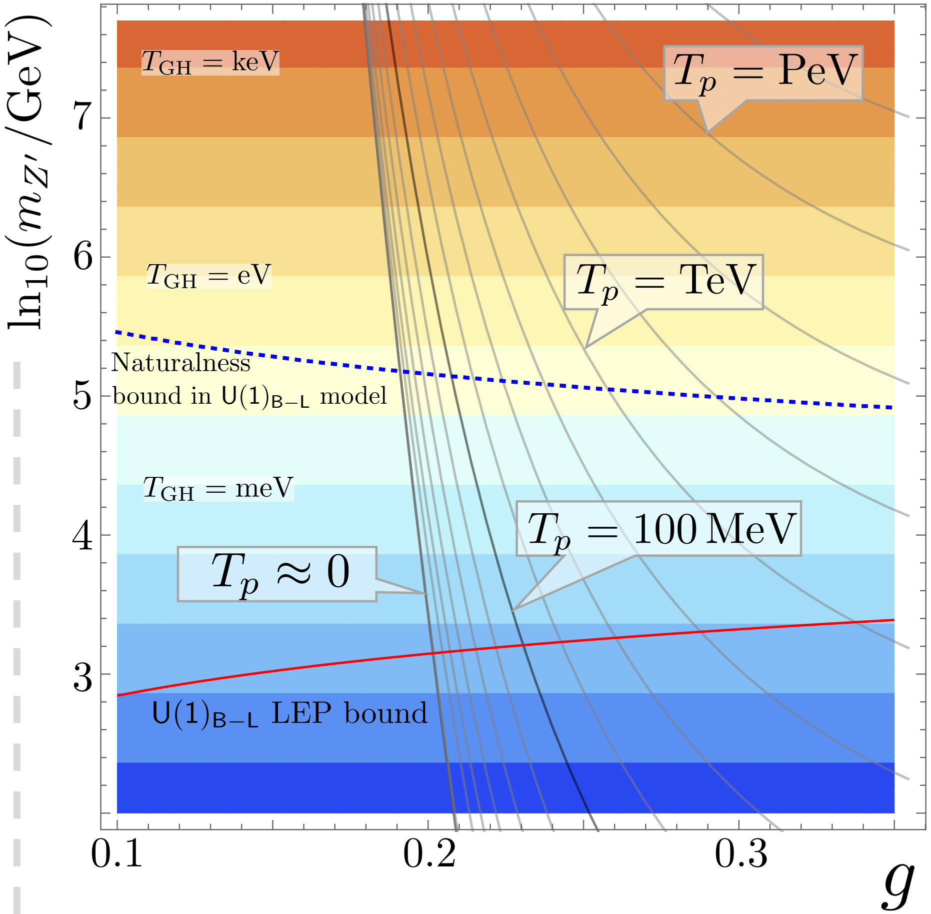
g : gauge coupling

$m_{Z'} \gg m_N$

Thermal barrier

height $\sim T^4$

thickness $\sim T/g$



Contour lines

T_p : percolation temp.
at which
universe is occupied
by true vac. bubbles.

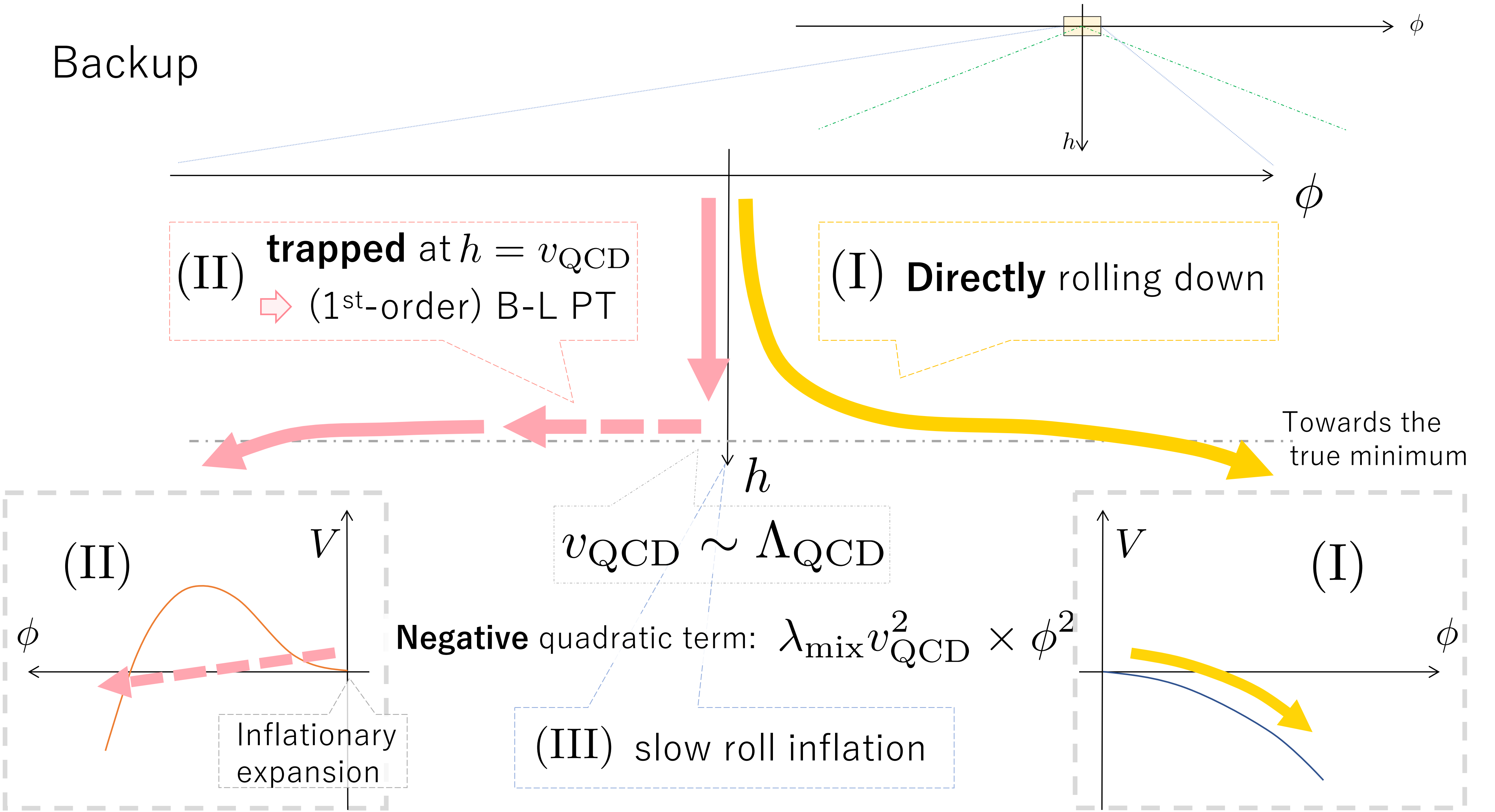
For $g \lesssim 0.2$,

EW (B-L) PT
is never completed.

$T_{\rm QCD} \sim 100\,\mathrm{MeV}$

QCD PT
takes place first.
(in most part of the universe)

Backup

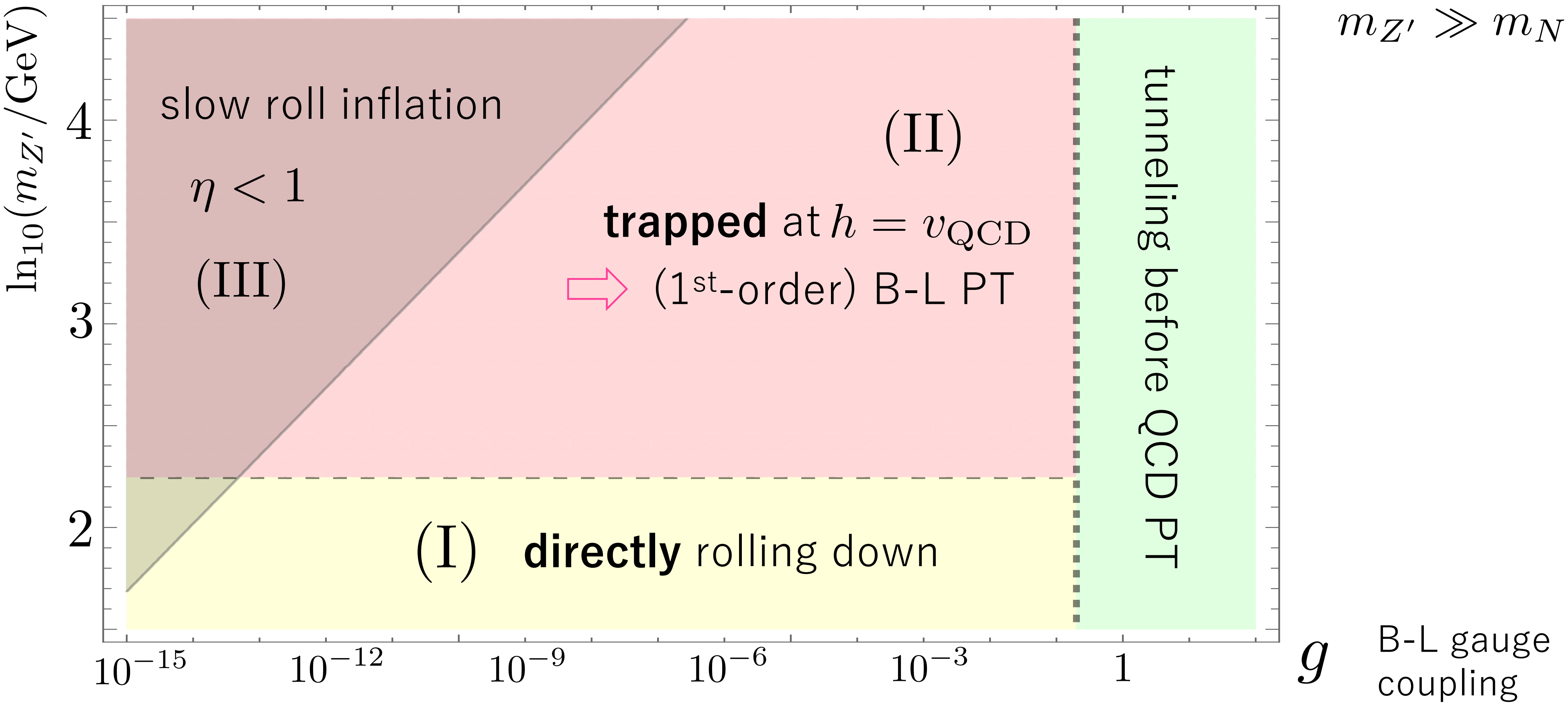


ϕ
h
ϕ
(II) **trapped** at $h = v_{\rm QCD}$
(1st-order) B-L PT
(I) **Directly** rolling down
Towards the true minimum
h
$v_{\rm QCD} \sim \Lambda_{\rm QCD}$
(II)
V
ϕ
Inflationary expansion
Negative quadratic term: $\lambda_{\rm mix} v_{\rm QCD}^2 \times \phi^2$
(III) slow roll inflation
V
(I)
ϕ

Backup

Minimal **U(1) B-L** model

$m_{Z'} \gg m_N$



Backup

Upper bound
on the temp. after the PT.

$$T_{\mathrm{i}} \equiv \left(\frac{30V_0}{g_* \pi^2}\right)^{1/4}$$

$$> T_{\max} > T_{\mathrm{rh}}$$